Ecological Modelling 363 (2017) 157–171

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Building emergy analysis of Manhattan: Density parameters for high-density and high-rise developments

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ARTICLE INFO

Article history:
Received 20 December 2016
Received in revised form 15 August 2017
Accepted 16 August 2017
Available online 14 September 2017

Keywords:
Emergy synthesis
Self-organization
Sustainable urban form
Square foot based building material quantity

ABSTRACT

To better understand how cities work, this study performs emergy (spelled with an “m”) synthesis of buildings on Manhattan Island. Conventional emergy studies have focused on much larger unit of analysis; however, architects, urban designers, and policymakers are operating on a smaller scale of building, block, neighborhood, and district. This study contributes to overcoming the scale and resolution mismatch between the macro- and micro-levels. Overall emergy for entire buildings on Manhattan Island is computed by adopting square-foot-base building cost estimation technique to emergy synthesis. We found that high-density and high-rise developments can achieve their maximum empower at the range of 1–5 Floor Area Ratio (FAR; an indicator of development density computed as total building floor area divided by total parcel area) and building height under 40 stories.

1. Introduction

With the increasing threats of climate change and steady increase in urban populations, sustainability has become a central focus of contemporary urban planning. Urban planners have emphasized a comprehensive approach in dealing with sustainability, including environmental durability, economic soundness, and social diversity (Berke, 2002, p. 30). However, actual policy interventions have focused on actionable solutions for discrete problems in building and transportation to conserve energy. A good example is the recent interest in autonomous electric cars. Instead of addressing a comprehensive change in systems to reorganize urban settlements for self-sufficiency, electric car initiatives intend to replace gasoline-fueled cars with electric cars that use electricity from renewable sources. This limited approach fails to address the underlying problems of dispersed settlement patterns and other urban issues of exclusion and class separation.

Urban issues are rarely isolated, wholly interconnected with each other (Odum, 2007; McHarg, 1969). For example, a community with higher density and mixed land use reduces the need for and the distance to travel (Jenks and Jones, 2010). As communities are connected with the city center and other communities, people have better access to public transit, further reducing transport energy (Cervero, 1998). With improved access and connectivity, the city center benefits from increased diversity and specialized labor that leads to economic growth through the agglomeration economy (Jacobs, 1961; Glaeser, 2011). Cities are complex ecological, economic, and social systems whose tendencies dramatically exceed the intentions of planners, politicians, and citizens. Therefore, a more comprehensive approach is necessary to understand the dynamics among density, land use, and transportation in cities.

What is an appropriate density, mix of land uses, and configuration of connectivity to minimize resource intake while continuing to be productive? What is an appropriate level of energy consumption per capita? This study seeks to answer these questions by analyzing the energy flow of buildings in Manhattan. We use the techniques of emergy (with an “m”) analysis to understand the interaction among urban form matrices; the four urban form matrices include density, land use mix, connectivity, and accessibility. Different accounting methods such as exergy analysis, embodied energy analysis, and life cycle analysis (LCA) each have their place, and each considers different boundaries of analysis. Emergy analysis considers the entire upstream contributions of work, energy, and materials, including environmental energies, which are typically discounted or considered to be free (Buranakarn, 1998; Brown and Buranakarn, 2003). Emergy analysis is more than another sustainability metric to be compared to norms or established as a goal; it is a research methodology for understanding the structure and purpose of complex, self-organizing systems. By evaluating the total inputs, outputs, and potential environment impacts of a product or process (Srinivasan and Moe, 2015), this comprehensive energy accounting method helps us to understand the hierarchies and interactions that emerge as systems grow, develop, and adapt to changing circumstances. In this respect, emergy and life-cycle

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http://dx.doi.org/10.1016/j.ecolmodel.2017.08.014
0304-3800/

concept provide insight into the nature of urban form and the total resource flows used to sustain it.

Emergy accounting is a top-down approach to account for inputs and outflows in a unit of analysis (Brown and Ulgiati, 2004, p. 331). It is an effective tool for understanding the relationships among urban elements and industries for large units, such as cities and regions; however, studies in smaller scale are less effective because of limited data and available information. This is a challenge for architects, planners, and urban designers who operate on a much smaller scale, buildings, blocks, neighborhoods, and districts. A new tool to overcome the gap in scale will help scholars and policymakers to assess and evaluate the effect of design and policy interventions. This study prepared an emergy synthesis of individual lots and block-level tracking of transportation, building operations, material, and monetary flow in New York City (Fig. 1).

2. Data and method

Emergy analysis is a useful tool for evaluating the overall sustainability of a system. Odum (1996) introduced the term emergy as a uniform measurement of energy and material flow. Formerly known as embodied energy (Huang et al., 1998; Brown and Ulgiati, 2004a; Brown and Ulgiati, 2004b), emergy is a cumulative accounting of available energy, a measure of the maximum useful work possible, captured and consumed in a process from its origin to its present state (Odum, 1996). That is, emergy synthesis of a building accounts for all energy spent to produce its raw materials, including wood, reinforced steel bars, concrete, and many others, as well as the energy taken to build its structure, labor, equipment use, and transport. Because emergy analysis uses a single unit of measurement—the solar emjoule (sej), or the amount of incoming available solar energy aggregated in raw materials—it allows for direct comparison of different processes and products (Srinivasan and Moe, 2015). In this respect, emergy synthesis is widely adopted to evaluate the sustainability of various industries, including agriculture (Odum, 1983; Sergio et al., 1994), trading (Odum, 1983; Brown, 2003), and tourism (Lei and Wang, 2008; Lei et al., 2011). Increasingly, environment impacts and policy effects are examined using emergy analysis (Almeida et al., 2007; Liu et al., 2011; Brown, 2014).

Emergy analysis has been extensively employed to study spatial organization and urban development pattern, mostly at the macro level: regional scale (Brown, 1980), state scale (Daniel and Ohrt, 2009; Campbell et al., 2004), metropolitan level (Huang et al., 1998), and city level (Odum et al., 1995; Lei et al., 2008; Ascione et al., 2009). At the micro level, emergy analysis became famous among architects and building systems engineers for expanding the boundary of life-cycle cost analysis (LCA) beyond the production and disposal phase of products (Brown and Buranakarn, 2003; Ravi et al., 2012; Srinivasan and Moe, 2015; Braham, 2015). Because finer resolution of emergy analysis introduces significant noise, a rigorous standardization would be helpful for emergy analysis of buildings (Braham and Benghi, 2016).

A few performance indicators have been developed to evaluate and compare systems (Odum, 1996; Brown and Ulgiati, 2004a; Brown and Ulgiati, 2004b; Brown, 2005; Brown and Vivas, 2007). These performance measures pay attention to the source of energy (renewable and nonrenewable) and to its location, inside or outside of system boundaries. Emergy yield ratio (EYR) is the ratio of total emergy input into a system, nonrenewable (N), renewable (R), and imported emergy (F), to the imported emergy: $EYR = (R + N + F)/F$. An EYR close to 1 indicates that few local resources were used in the system. Environmental loading ratio (ELR) is an indicator of potential pressure on the environment. The notion of ELR is evolving (Lu et al., 2014, 2017). The earlier notion of ELR was a ratio of imported resources, e.g. imported fossil fuel, spent over local renewable energy: $ELR = (N + F)/R$ (Brown and Ulgiati, 1997). The definitions of imported resources and local renewable energy are specified to cover resources that are related to the environment. Odum (1996) added imported materials (M_N) and imported services (S_N) to replaced imported resources (F): $ELR = (N + M_N + S_N)/R$. Ortega et al. (2002) proposed matching the kinds of energy sources for both imported and local energy (R), M_N, S_N, local materials (M_R), and local services (S_R): $ELR^* = (N + M_N + S_N)/(R + M_R + S_R)$. The current definition of ELR is expanded to distinguish pre- from post-process distinguishing environmental load that is taken in the treatment system (foreground) and that is taken beyond the treatment process (background) on a larger scale. The Environmental Sustainability Index (ESI) is useful for measuring how a system changes its source of energy to sustain its economy. ESI is represented as EYR divided by the ELR: $ESI = EYR/ELR$, $ESI^* = EYR/ELR^*$. Both ESI and ESI* are useful indicators to show how societies became dependent on fossil fuel or imported materials and services over time.

Empower densities for a site area (ED-site, sej/yr/m^2), building area (ED-bldg, sej/yr/m^2), and per capita (EC, sej/yr/person) are more effective measurements for comparing similar urban systems. Urban blocks in Manhattan are almost identical in retaining the original grid plan of Manhattan (Reps, 1965); therefore, the renewable input of wind, rain, and sunlight are roughly the same. Furthermore, the renewable input is almost negligible to external energy input for each parcel. ED is a measurement for gauging spatial hierarchy; this is the ratio of total emergy use over the total area of the system. Cities show an empower density gradient from the center to the periphery; higher ED is in the center, and decreases as the distance increases from the center (Brown, 1980; Huang et al., 2001). Empower density is highly correlated with land use because zoning regulations follow the density gradient from the center as well.

Emergy synthesis at a finer resolution is not a new concept. Braham and Yi (2015) first introduced emergy synthesis at the building level by separating inputs into three scopes or scales of activities: site, shelter, and setting. Renewable emergy inputs such as sunlight, wind, and rainwater geo/chemical potential account for most of the site input. Researchers estimate the total weight of a building by examining the building plans, cross sections, and digital building information models (BIMs). Then the material quantity is multiplied by corresponding material unit emergy values (UEVs) to calculate the annual depreciation of a building's emergy or shelter. To estimate annual depreciation, individual building components are separately calculated using different expected lifespans. For interior finishes and mechanical and electrical systems, the expected lifespans are standardized. However, the lifespans of exterior walls and structural components are correlated with building age. When the age of a building exceeds its expected lifespan, the building age is used in place of the expected lifespan to calculate the annual depreciation of building structures.The setting is accounted for by estimating resource consumption, including water, food, durable goods, and utility based on demographic data with the depreciation of the building interior (Braham, 2016).

This study expands individual building emergy synthesis to multiple buildings, districts, and city-wide analysis. While emergy accounting of individual buildings provides greater accuracy and detail, accounting for over 40,000 buildings in the Manhattan borough in New York City is a time-consuming task, even with the help of advanced building digital models. Instead, we adopted a building cost-estimating practice to calculate the overall quantity of building materials, labor hours, and resources by individual buildings, using publicly available tax data, GIS shapefile, and RSMeans square foot cost data (see Appendix-A and Fig. 2). Similar to building emergy analysis the overall emergy value for each building is